Temperature dependent properties of an anisotropic Mn-Al-C permanent magnet

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The anisotropy field, coercivity and saturation magnetization in a Mn-Al-C permanent magnet were measured as a function of temperature from 4.2K to 300K. The coercivities in both the easy and hard directions were found to decrease linearly with temperature with slightly different slopes. The coercivities measured with the applied field along the hard direction were found to exceed those obtained when the field was aligned with the easy axis. A model for the mechanism producing this effect is discussed. The anisotropy field is found to decrease linearly with temperature while the reduced saturation magnetization follows a $-T^{3/2}$ law.

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INTRODUCTION

Recently there has been a great deal of interest in the permanent magnetic materials in the system Mn-Al-C due to the broad availability and relatively low cost of the constituents and its impressive magnetic properties. The ferromagnetic properties of Mn-Al were first investigated in the late 1950s and early 1960s (1, 2, 3). Kojima, et al (4) found that the addition of carbon stabilizes the τ phase up to about 700°C for extended times - thus permitting high temperature swaging. An anisotropic polycrystalline magnet (70 wt% Mn, 29.5 wt% Al, 0.5 wt% C) having magnetic properties of B_r =6100G, $_IH_c$ =3000 Oe, $_BH_c$ = 2700 Oe, and $(BH)_{max}$ ~7MGOe, and good machinability, was produced by the Matshushita Electric Industrial Company (5). It appears that the addition of carbon limits the grain growth and thus the grain size to approximately 1μm, making the material more ductile. The coercive force now appears as a result of the combination of impeded domain wall nucleation within the relatively ordered crystalline grains and domain wall pinning of the resultant walls at the grain boundaries. Since for many potential applications it is desirable to understand the temperature dependence of the magnetic properties, it was decided to obtain such data.

MEASUREMENTS AND RESULTS

Using a 3mm cube of permanent magnet material of the composition 70 wt% Mn, 29.5 wt% Al, 0.5 wt% C, furnished by the Matshushita Electric Industrial Co. of Japan, we have made M vs H loop measurements in both the hard and easy directions from liquid helium to room temperature using an integrating flux meter in conjunction with a superconducting magnet which allows application of external fields up to 100 kOe (6). The M vs H loop measurements in the hard direction were made by applying our external field in this direction with sufficient intensity to saturate the sample perpendicular to the easy axis - then decreasing the field to zero and reversing the field to saturate the sample in the negative hard direction. We note that this differs from experiments which first saturate the sample in the easy direction and then determine the coercivity by applying the field at angles such as 90° to the axis (7). The uncorrected anisotropy field was taken to be equal to the applied field beyond which there was no further discernible change in magnetization. Corrections for the demagnetization effect were made and were about 2 kOe (6). It was assumed that the demagnetization factor for a sphere was applicable. From these measurements we have been able to extract, as a function of temperature, the intrinsic coercivity (Figure 1), saturation magnetization (Figure 2), and anisotropy field (Figure 3).

From Figure 1 we note that the coercivity in the hard direction is greater than that in the easy direction. Further, we note that the coercive force in both directions exhibits a linear decrease in magnitude as the temperature is increased, but with slightly different slopes.

The saturation magnetization, M_s (Figure 2), appears to follow the expression

$$\frac{M_s}{M_s(0)} = 1 - \frac{1}{3}\left(\frac{T}{T_c}\right)^{3/2} \qquad (1)$$

where T_c = 380 C (8). The anisotropy field, H_A, also decreases with temperature but in a linear fashion.

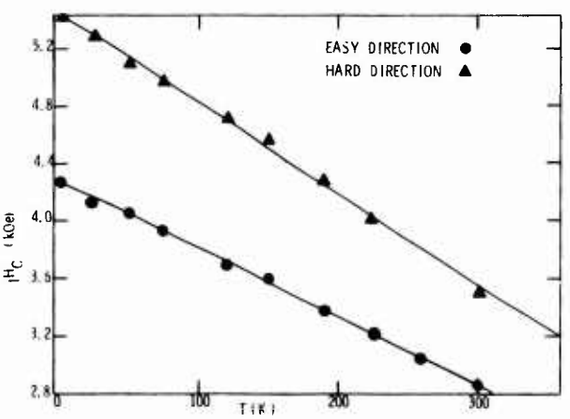

Figure 1. Coercivity vs temperature for Mn-Al-C (intrinsic)

DISCUSSION

The linear drop in the coercive force as a function of temperature may be the result of two contri-

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butions: 1) the drop in the value of the anisotropy field and the magnetization as the temperature is increased and 2) the increase in the thermal vibrational energy of the ferromagnetic domain walls as the temperature increases.

The first contribution can be estimated using the formula for the coercive force

$$H_c = \left(\frac{H_A}{3}\right)^{3/2}\left(\frac{M_s}{6A}\right)^{1/2} W(\eta+\alpha) \quad (2)$$

obtained by Paul (9) and applicable to domain wall pinning by defects of narrow width W and small anisotropy and exchange deviations, η and α, from the host material. The quantities H_A and A are the host anisotropy field and exchange constants. One must also estimate the effect of contributions above to the coercive force due to the reduced difficulty in nucleating domain walls. For this we do not yet have any analytic expression.

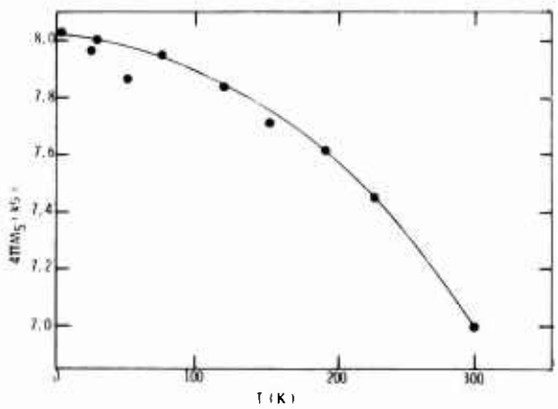

Figure 2. Saturation magnetization vs temperature for Mn-Al-C

The second possible contribution (the increase in the thermal vibrational energy) was considered by Gaunt (10) who showed that the change in the coercive force as a function of temperature due to this mechanism could be written as

$$\Delta H_c = -25k_BT/MA'W \quad (3)$$

where A' is the domain wall area. The magnitude of ΔH_c in this formula is difficult to estimate without a knowledge of the other parameters. We note, however, that it does predict the linear dependence on the temperature as is observed experimentally.

The higher H_c in the hard direction is explainable in terms of incomplete alignment of all the easy axes of the individual grains. Sakamoto (11) has shown that M_r/M_s was $\sim$ 0.88 from magnetization measurements, while M_r/M_s = 0.87 was found in the present work; both indicative of incomplete alignment.

Due to the particularly small size of the grains (1 μm), the grain boundary pinning mechanism probably makes a substantial contribution. When the material is saturated in the hard magnetic direction and the field released or reversed, the usual initial process is magnetic moment rotation towards the easy direction (remembering that domain walls do not form parallel to the hard direction). However, those moments located at areas of local misalignment, θ, of the easy axis

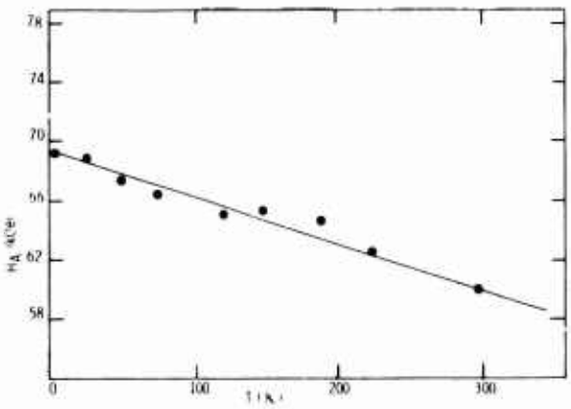

Figure 3. Anisotropy field vs temperature for Mn-Al-C

require an applied field varying as $(\cos\theta)^{-1}$ (12, 13) to overcome the anisotropy field. Therefore, although there is a rapid drop in the remanent-magnetization caused by the rotation to the easy axis of large numbers of magnetic moments, upon release of the external field, the reverse field necessary to "unpin" the remainder of the magnetic moments such that M equals zero (i.e., $H = H_c$) is quite high.

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